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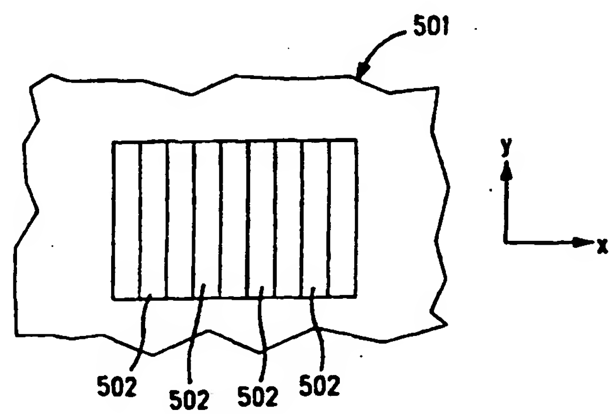
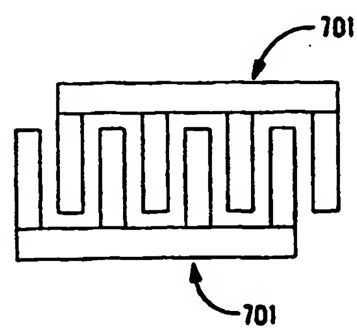
(54) Title: HIGH FREQUENCY SURFACE ACOUSTIC WAVE DEVICES FOR RADIO FREQUENCY APPLICATIONS AND THE METHOD OF FABRICATING THE SAME

(57) Abstract

A device, and the related method of fabricating such a device, for generating surface acoustic waves (SAW) based on interdigitation of electrodes. The device has a line width and spacing of quarter wavelengths on the order of 100 nanometers or less to enable operation at frequencies above 10GHz. In operation, the device can be modified to effect very narrow bandwidth, high frequency rf filters, as well as modulators, convolvers and other devices used for signal processing. Because the electrode structure of the device are both narrow in dimension, as well as uniform in size, the opportunity for propagation of other than the desired frequency is minimized. To this end, because of the uniformity of line-width and line spacing, very accurate quarter wavelength devices can be fabricated. This reduces the possibility of a device supporting other wavelengths in the surface acoustic wave medium, thereby narrowing the bandwidth of the devices. The narrow bandwidth, and thereby narrow frequency response, of the device enable high speed operation. To this end, it is clear that devices based on accurate wavelength dependent structures, for example quarter wavelength SAW filters, can be fabricated.





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High Frequency Surface Acoustic Wave Devices for Radio Frequency Applications and the Method of Fabricating the Same

Field of the Invention

The present invention relates to surface acoustic wave devices for high frequency applications and the method of fabricating the same.

Background of the Invention

Miniature radio frequency filters, as well as other devices, are needed to reduce the size and weight of portable equipment for mobile communications. Filters and other devices based on surface acoustic waves are inherently smaller than devices based on other filtering techniques, since the wavelength of an acoustic wave, in typical media, is 10^5 smaller than the wavelength of electromagnetic waves at the same frequency. Surface acoustic wave (SAW) devices use piezoelectric materials to convert electromagnetic signals, in this case generally rf signals, to mechanical surface acoustic waves in the particular material. These devices can be used as filters, for example, by establishing a resonant "cavity" between reflectors. Only surface acoustic waves with the requisite resonant frequency of the cavity will propagate in appreciable magnitude. In operation, a sending transducer converts electromagnetic radiation into a mechanical surface acoustic wave, and a pick-up electrode converts the mechanical wave to an electromagnetic wave, in this case an rf wave. Other devices based on this principle, can be effected as well. For example, by effecting the phase shift, a delay line can be effected. Additionally, a modulator or a convolver, as well as other devices for signal

processing for rf signals can be effected by variations of the principals stated above.

The basic structure of SAW devices consists of two interdigitated comb-like electrode patterns. The width and separation of each of the electrodes is one-quarter wavelength of the propagating acoustic waves in the direction perpendicular to the grating. This is as shown in Figure 1. The surface acoustic waves are excited by applying a voltage to the electrodes, with the frequency given by:

$$f\lambda = v \quad (1)$$

Where f is the frequency of propagation, λ is the wavelength and v is the velocity of the surface wave in the particular material used for the filter or other device. A second interdigitated electrode structure is disposed at a given position depending upon the device chosen, for detecting the surface acoustic waves and converting the mechanical wave back to an electrical wave. In a particular application, where an rf filter is desired, a set of electrodes, which effect the sending transducer for converting the rf signal into an acoustic wave and a set of electrodes which converts the S.A.W. wave into an rf signal is disposed to effect the receiving transducer. These transducers, the sending and receiving transducers, are situated between reflectors, which form the resonant cavity, as described above. The length of the fingers of the electrodes may be varied to achieve the desired characteristics, for example, bandwidth, side lobe suppression and shape factors, as can be appreciated by one ordinary skill in the art. Based on these concepts, band pass filters, comb filters, modulators, pulse compressors, convolvers, correlators and other devices to effect signal processing, have been developed.

As can be appreciated, the operating frequency of surface acoustic waves, particularly at high frequency, is limited by the achievable line spacing and width of

the electrodes, which is dependent upon the wavelength of the surface acoustic wave in the particular material utilized for the device. Figure 2 shows the line width/spacing of surface acoustic wave devices that is required for different materials as a function of frequency. As can be seen, for operation at one GHz, the required width and spacing of the electrodes is one micron with the commonly used $LiNbO_3$ substrates for surface acoustic wave devices. A miniature surface acoustic wave filter, having dimensions on the order of $3.2x2.5x.9mm^3$, capable of 950MHz operation, has been produced by flip chip assembly techniques. However, using present state of the art 0.35 micron optical lithography, with a line width and spacing of 0.5 microns, the achievable operating frequency is limited to about 2GHz. For higher operating frequencies, other lithography methods, such as e-beam direct right and x-ray lithography, have been used. Unfortunately, these techniques have a great deal of drawbacks, which would impact their effectiveness in commercial applications. The e-beam direct right technique can be used to form fine geometries required for high frequency applications of surface acoustic waves, but this technique has a throughput which is low and perfect stitching over large areas is very difficult. X-ray lithography may be used but it is a very complicated process by virtue of difficult masking and resist requirements.

Accordingly, to meet the need for communication systems operating at frequencies higher than 2GHz, a technique for fabricating narrow electrodes with narrow line spacings, is needed to produce surface acoustic wave devices at a low cost.

Summary of Invention

The present invention is drawn to miniature radio frequency surface acoustic wave devices based on

interdigitation of electrodes. The devices of the present invention have line width and spacing of quarter wavelengths on the order of 100 nanometers or less to enable operation at frequencies above 10GHz. The disclosure of the present invention envisions the use of various materials as the medium for propagation of surface acoustic waves. To this end, while lithium niobate is the preferred material in most devices of the present disclosure, large scale integration of the rf surface acoustic wave devices of the present disclosure into integrated circuits would clearly enable AlN as an alternative material to lithium niobate. In operation, the devices of the present disclosure can be modified to effect very narrow bandwidth, high frequency rf filters, as well as modulators, convolvers and other devices used for signal processing. Because the electrode structure of the devices of the present disclosure are both narrow in dimension, as well as uniform in size, the opportunity for propagation of other than the desire frequency is minimized. To this end, because of the uniformity of line-width and line spacing, very accurate quarter wavelength devices can be fabricated. This reduces the possibility of a device supporting other wavelengths in the surface acoustic wave medium, thereby narrowing the bandwidth of the devices. The narrow bandwidth, and thereby narrow frequency response, of the devices of the present invention enable high speed operation with bandwidth resolution not achievable in the prior art. While rf filters are the primary focus of the disclosure of the present invention, other devices as mentioned above can be readily made through adaptation of the method of manufacture disclosed herein. To this end, it is clear that devices based on accurate wavelength dependent structures, for example quarter wavelength SAW filters, can be fabricated.

In addition, the present invention also relates to a process for manufacturing high resolution surface

acoustic wave devices for rf and high frequency applications. While it is true that the preferred use for the method of the present disclosure is the fabrication of wavelength dependent SAW devices it is of course true that this method can be applied in general to achieve high resolution lithography. The technique utilizes fine optical interference patterns effected through basic physical optical principles with a very high resolution due to the narrow line width of the laser light source. A laser beam with a preselected wavelength is first expanded to the size of the desired exposure area with a beam expander. The expanded beam is separated into two beams, using a beam splitter and recombined at the wafer at the desired intersecting angle to produce the desired interference fringes. A shutter is placed in the path of the laser beam to control the exposure time. The interference pattern effected at the wafer exposes a photoresist disposed on top of the layer.

Because the light from a laser is coherent, the two intersecting beams will interfere at the wafer surface and establish a standing wave pattern that has a period depending upon the intersecting angle and the wavelength of the laser.

A photomask is used to effect the desired aperture of the device being fabricated by the present technique. After a first interference pattern is effected, the photomask is shifted laterally by one-quarter wavelength and by a desired distance in the vertical direction in order to fabricate the exposure pattern desired. A second exposure is carried out in the same fashion as the first exposure. The combined exposed area has the shape of an intersecting comb-like pattern to effect the interdigitation of the electrodes. To connect the alternate fingers, a third exposure is carried out.

After the requisite exposure of the photomask, standard metalization techniques are carried out in

order to fabricate the electrodes and electrical connections thereto. The resultant device is an interdigitated electrode pattern with the desired spacing and width to serve as the basic building blocks for launching and detecting surface acoustic waves in the chosen material.

The invention itself, together with further objects and attendant advantages, will best be understood by reference to the following detailed description taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

Figure 1 is a top view of a typical interdigitated electrode structure for transmitting surface acoustic waves in a piezoelectric material.

Figure 2 is a graphical representation of the line width/spacing in microns versus frequency in GHz for suitable materials for the disclosure of the present invention.

Figure 3 is a perspective view of the optical arrangement for effecting the interference pattern on the wafer of the present disclosure.

Figure 4 is a cross-sectional view showing the incident light effecting the interference fringes in the exposure of the photoexist.

Figure 5 is a top view showing the aperture defined by the photomask with the exposed resist patterns.

Figure 6 is a top view showing the exposed resist patterns after the second exposure.

Figure 7 shows the exposed resist patterns for connecting the individual electrodes.

Figure 8 show an alternative apodization by the teachings of the present invention.

Detailed Description of the Invention

The present disclosure is drawn to a technique based on multiple exposures of standard photoresist, either positive or negative, with light from a laser or other coherent light source which forms interference patterns on the photoresist at desired intervals. After a first exposure, an aperture is shifted corresponding to one quarter of the acoustic wavelength in the material with a precision mechanical stage. A second exposure forms a second set of interference fringes on the photoresist resulting in the interdigitation pattern desired. The patterns recorded on the photoresist, can then be transferred to a metal layer with either standard liftoff, etching or plating techniques.

To effect the resultant product of the present invention, a photoresist is deposited on the top surface of the wafer of material used for the S.A.W. device, preferably $LiNbO_3$, and a first exposure is affected as follows. While it is true that $LiNbO_3$ is preferred, other materials as shown in Figure 2 can be used for S.A.W. device applications. The optical system shown in Figure 3 has a laser, or other source of coherent light, preferably a HeCd laser with a wavelength on the order of 325 nanometers. The light from the laser 301 is impingement upon a lens 302 and beam expander 303 as shown in Figure 3. The coherent radiation 300 from the laser is split by a 50/50 beam splitter 304 and a portion of the beam is impingement upon a mirror thereafter to the wafer, while the other portion is directly impingement upon the wafer. The beam expander 303 is chosen to expand the light from the laser to the size of the desired exposure. The expanded beam is separated, as stated into two beams using a standard beam splitter and then recombined at the wafer 305 to effect the interference fringes. A shutter is placed in the path of the laser beam to control the exposure time.

A mechanical stage 306 with an accuracy on the order of one nanometer over a distance of 50 microns is used to move the sample to effect multiple exposures.

Because the light from the laser is coherent, the intersecting beams will interfere at the wafer surface with each other to set up a standing wave with a period that depends upon the intersecting angle and the wavelength; the period is described by the following:

$$p = \frac{\lambda}{n} (\sin\theta_1 + \sin\theta_2) \qquad (2)$$

Where p is the period of the pattern, n is the index of refraction of the photoresist, λ is the wavelength of the light and θ_1 and θ_2 are the incident angles of the light. With the exemplary helium-cadmium laser of the present disclosure, the 325 nanometer line has a shortest period on the order of 162.5 nanometers when the two beams are propagating towards each other in the plane of the wafer. The standing wave is used to expose the wafer coated with standard photoresist to record the pattern. The interference fringes effect exposure lines of high resolution in both width and spacing by virtue of the well defined wavelength and coherent light of the laser. Such results follow from standard principles of physical optics. As stated previously, the method of the present disclosure is applicable to other lithography applications. In particular, where linewidth and spacing resolution as well as uniformity are important features, the method of the present disclosure can be used as a photolithographic technique. It is clear that this technique is applicable to large scale IC fabrication and other fields of endeavor.

The key steps of the method of the present disclosure are as shown in Figure 5-7. For purposes of simplicity of example, a simple transducer structure will be explained fully. The disclosure of the present method is clearly applicable to other transducer

arrangements. Turning to Figure 5, a first exposure results in a pattern on the photoresist, due to the interference pattern established by the interfering light. The first exposure is confined in a square aperture defined by the quartz photomask 501, with regions of constructive interference as shown at 502. As stated earlier, either positive or negative photoresist techniques can be used. Additionally, depending upon the application and the resist, metal deposition can be effected first and thereafter standard etching techniques can be used to reveal the electrodes. Additionally, the metalization can be effected after the resist step by standard liftoff techniques or a standard plating technique.

The photomask 501 is anti-reflective coated to minimize reflection at the wavelength of light from the light source and the incident angle. After the first exposure, the wafer is mechanically shifted by one quarter of the wavelength of the surface acoustic wave in the material in the direction normal to interference lines and approximately 20 microns in the direction parallel to the interference lines, as shown by arrows x and y, respectively. The exposing laser beam and photomask remain stationary during the movement. After the movement of the wafer, a second exposure is effected in the same manner as the first exposure. The combined exposed area has the shape of the intersecting comb-like pattern, as is shown in Figure 6. The exposed resist shown at 601 and 602 for the two sets of electrodes have width and spacing of one-quarter wavelength. A third and final exposure is effected to connect the alternate fingers, as is shown in Figure 7 at 701. After the third exposure, a comb-like interlacing electrode pattern is revealed, and through standard metal liftoff or plating techniques, the basic building block for transmitting and detecting surface acoustic waves at high frequencies is effected.

To achieve the desired device characteristic, for example, a square filter, the length of the figures can be varied according to the desired weighting function by changing the shape of the aperture, defined by the photomask, in contact with the wafer. Since the weighting function is a slow varying envelope function, with no fine features, and there is no need to align the mask with the wafer. Therefore, simple photomasks with suitably defined patterns can be used to achieve the desired finger overlap. As an example, devices with twenty fingers weighted with a function given by

$$\frac{\sin(\chi)}{\chi};$$

yielding a square filter characteristic, as is shown in Figure 8. This is achieved with the aperture, as is shown in Figure 8. Other patterns, less and more complicated, can also be achieved by using apertures of different shapes. Using the method described above, complicated device structures can be built from the simple structure shown in Figure 5-8.

The achievable line width with the present method is less than or equal to 100 nanometers to allow operation of frequencies above 10GHz. The line width can be further reduced by increasing the number of exposures and reducing the offset distances. The uniformity of the grating spacing across the wafer can be readily achieved, since the laser wavelength is fixed and the incident beam angle can be kept constant by using precision optical elements. The result of the uniformity is a significant increase in yield and therefore a significant reduction in cost when compared to other techniques, which potentially could result in high resolution electrode structures, effected by e-beam and x-ray techniques, as described above. Furthermore, the production costs for surface acoustic waves fabricated with the present method is reduced since the laser beam can be expanded to cover the desired wafer

size and maintain the uniformity and across the entire wafer. When compared to alternative means to fabricate fine line electrodes for surface acoustic wave devices, the method of the present disclosure offers significant performance and cost advantages by allowing much less complicated equipment, higher uniformity and higher throughput, as well as a more convenient manufacturing process, by standard techniques well known to one of ordinary skill in the art.

The device fabricated as above, has a linewidth and spacing with dimensions and resolution which are both uniform across a wafer and of the required dimensions for high frequency applications. Because of the resolution and uniformity of the fabrication technique, the linewidth/spacing of the electrodes is precise with insignificant variation. Because of this, the devices of the invention of the present disclosure effect surface acoustic waves having well-defined wavelengths. The result in a filter, for example, is a slow narrow bandwidth.

The invention having been described to detail is clear that variations and modifications of the present disclosure are within the purview of one of ordinary skill in the art. To the extent that such modifications of the present disclosure, a technique for fabricating surface acoustic wave electrode structures, as well as reflectors on a suitable piezoelectric material for high frequency applications using optical interference patterns, such are deemed within the scope of the present invention.

Of course, it should be understood that a wide range of changes and modifications can be made to the preferred embodiment described above. It is therefore intended that the foregoing detailed description be understood that it is the following claims, including all equivalents, which are intended to define the scope of this invention.

Claims

I Claim:

1. A device for generating surface acoustic waves for applications comprising:

a first interdigited electrode having a plurality of digits (601) forming a comb-like electrode pattern, wherein said digits are interconnected (701) at one end;

a second interdigited electrode having a plurality of digits (602) forming a comb-like electrode pattern, wherein said digits are interconnected (701) at one end;

said electrodes interleave with one another, wherein said digits of each of said respective electrodes being aligned between said digits of opposing electrode, defining resonant space there between said digits;

said digits having a width of about a one-quarter wavelength equating to less than 100 nanometers; and

said resonant space having a dimension of about a one-quarter wavelength equating to less than 100 nanometers.

2. A method of fabricating a device for generating surface acoustic waves at a predetermined wavelength, the method comprising:

disposing photoresist on surface of a wafer (305);

separating a beam from a stationary coherent light source (301) into separate beams (300) and recombining said beams to interfere at the surface of said wafer (305) to set up a standing wave with a period that depends upon the intersecting angle on said wafer (305) and the wavelength, the period is defined by

$$p = \frac{\lambda}{n} (\sin\theta_1 + \sin\theta_2)$$

wherein p is the period of the pattern, n is the index of refraction of the photoresist, λ is the

wavelength of the light and θ_1 and θ_2 are the incident angles of the light;

first exposing said wafer (305) for a prescribed time producing first interference fringes (502), said first exposure confined in an aperture defined by a stationary photomask (501), said first interference fringes (502) forms a first interference pattern on said wafer (305), said first interference pattern effects a first interdigited electrode (601) on said wafer (305), said first interdigited electrode (601) includes a plurality of digits having a comb-like electrode pattern;

shifting said wafer by one-quarter of the wavelength of the acoustic wave in a direction normal to said digits and approximately 20 microns in a direction parallel to said digits; and

secondly exposing said wafer for a prescribed time producing second interference fringes (502), said second exposure confined in an aperture defined by said stationary photomask (501), said second interference fringes (502) forms a second interference pattern on said wafer (305), said second interference pattern effects a second interdigited electrode (602) on said wafer (305), said second interdigited electrode (602) includes a plurality of digits having a comb-like electrode pattern.

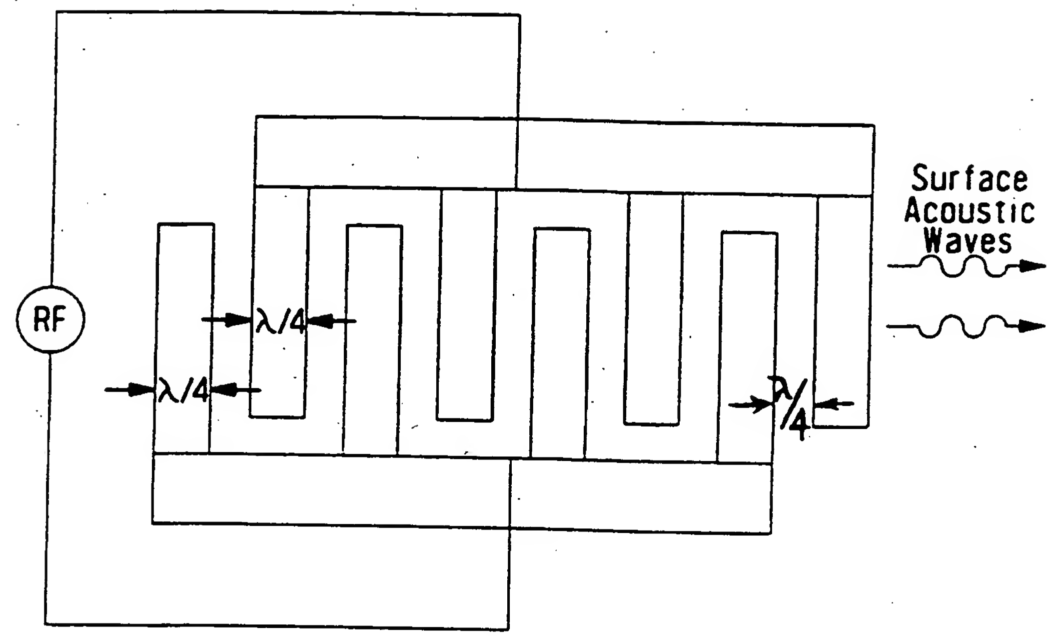

Surface
Acoustic
Waves
RF
λ/4
λ/4
λ/4

Fig. 1

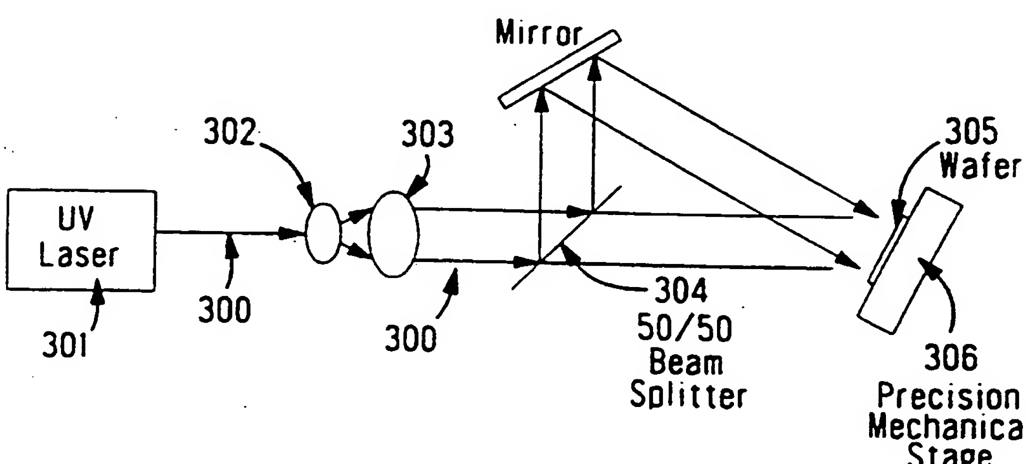

Mirror
302
303
305
Wafer
UV
Laser
301
300
300
304
50/50
Beam
Splitter
306
Precision
Mechanical
Stage

Fig. 3

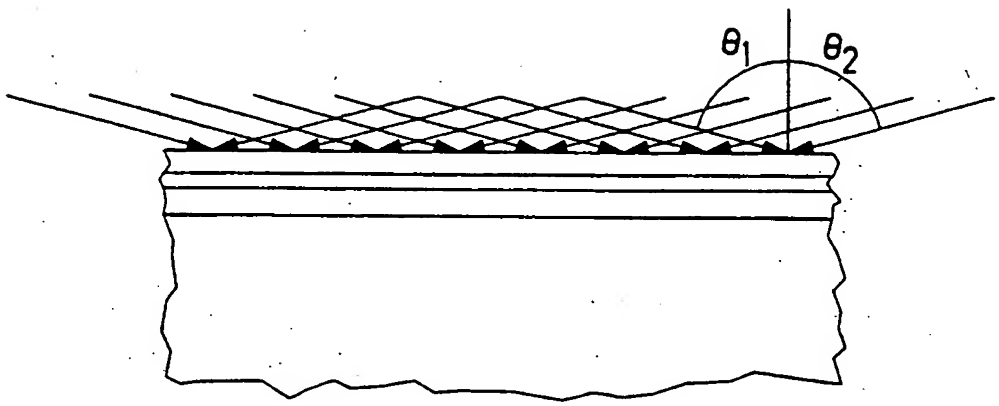


Fig. 4

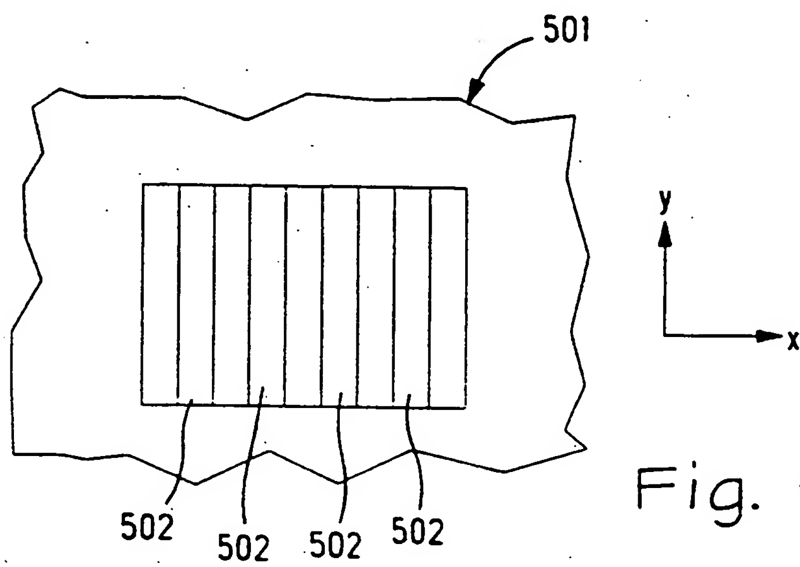


Fig. 5

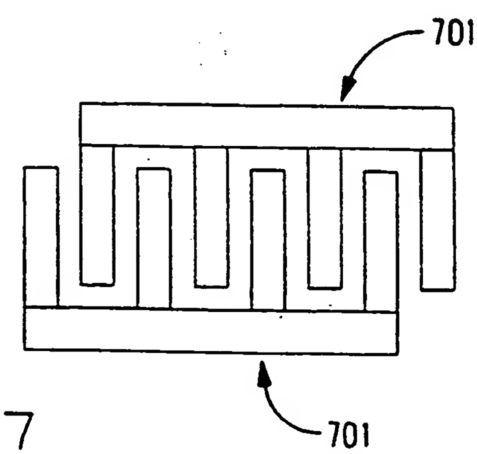
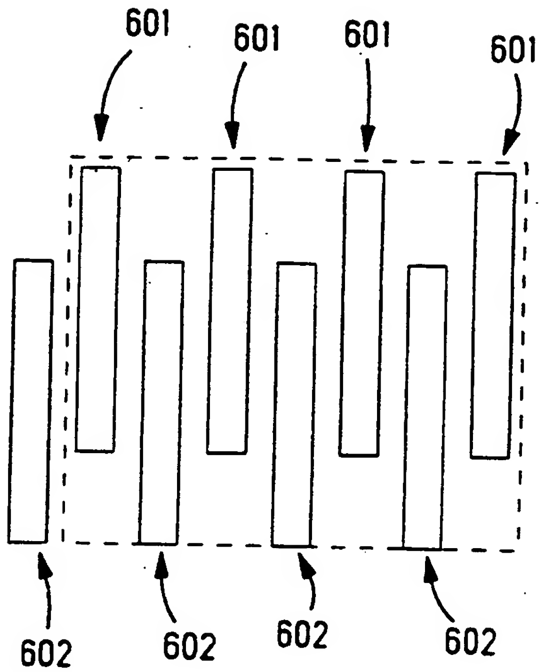


Fig. 7

Fig. 6



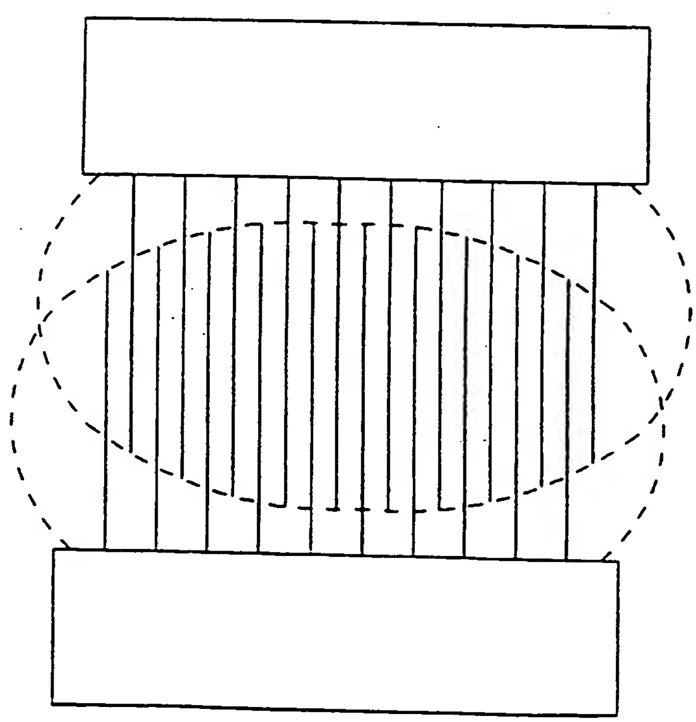


Fig. 8

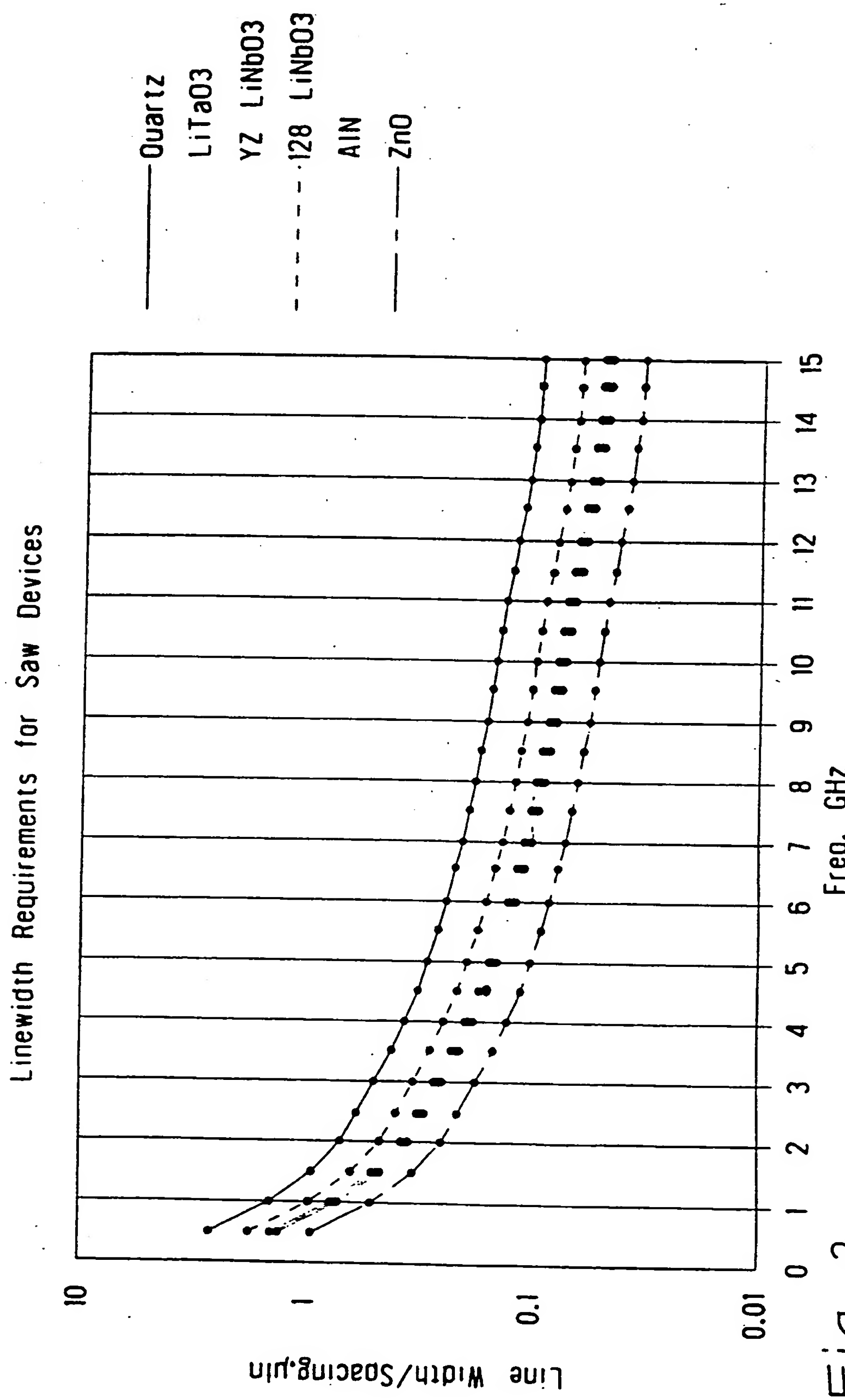

Linewidth Requirements for Saw Devices
Quartz
LiTaO3
YZ LiNbO3
128 LiNbO3
AlN
ZnO
Line Width/Spacing,µm
10
1
0.1
0.01
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Freq. GHz

Fig. 2

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/08793

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H03H3/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H03H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	YAMANOUCHI K ET AL: "NANOMETRE ELECTRODE FABRICATION TECHNOLOGY USING ANODIC OXIDATION RESIST FILMS AND APPLICATIONS TO 10GHZ SURFACE ACOUSTIC WAVE DEVICES" ELECTRONICS LETTERS, vol. 30, no. 12, 9 June 1994, pages 1010/1011-1011, XP000459810 see the whole document ---	1

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[ ] Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
8 July 1998	16/07/1998

Name and mailing address of the ISA	Authorized officer
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Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/08793

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	YAMANOUCHI K ET AL: "NANO-METER ELECTRODE FABRICATION TECHNOLOGY USING ANODIC OXIDATION RESIST AND APPLICATION TO 20 GHZ-RANGE SAW DEVICES" PROCEEDINGS OF THE ULTRASONICS SYMPOSIUM, BALTIMORE, OCT. 31 - NOV. 3, 1993, vol. VOL. 2, no. -, 31 October 1993, LEVY M;MCAVOY B R, pages 1263-1266, XP000475286 see the whole document	1
A	YAMANOUCHI K ET AL: "NANOMETER-FABRICATION PROCESS AND GHZ-RANGE LOW-LOSS SAW FILTERS" ELECTRONICS & COMMUNICATIONS IN JAPAN, PART II - ELECTRONICS, vol. 76, no. 6, 1 June 1993, pages 42-50, XP000420498 see the whole document	1,2

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